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THE EFFECTS OF BASE BLEED AND SUSTAINER ROCKET NOZZLE DIAMETER AND LOCATION ON THE BASE DRAG OF A BODY OF REVOLUTION WITH CONCENTRIC BOOST AND SUSTAINER ROCKET NOZZLES

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THE EFFECTS OF BASE BLEED AND SUSTAINER ROCKET NOZZLE DIAMETER AND LOCATION ON THE BASE DRAG OF A BODY OF REVOLUTION WITH CONCENTRIC BOOST AND SUSTAINER ROCKET NOZZLES

By

Charles E. Brazzel

AMC Management Structure Code No. 5210.11.148

Aerodynamics Branch
Advanced Systems Laboratory
Future Missile Systems Division
Directorate of Research and Development
U.S. Army Missile Command
Redstone Arsenal, Alabama

ABSTRACT

A concentric arrangement of boost and sustainer rocket nozzles has been investigated to determine the effects of base bleed and the effects of sustainer nozzle diameter and relative longitudinal position on the base drag of the body during sustainer operation. The results of the investigation indicate that the jet-on base drag of a body can be significantly reduced by the use of base bleed and nozzle arrangement, and that the jet-on base drag is a function of the jet thrust.

The data presented are based on the results of tests in the Aberdeen Ballistic Research Laboratories 13 by 15 inch supersonic wind tunnel at Mach numbers of 2.0 and 2.5. The model tested had sustainer nozzle-to-base diameter ratios of 0.10, 0.20, and 0.30, and boost nozzle-to-base diameter ratio of 0.80. The sustainer nozzle was tested at longitudinal positions between 0.60 calibers aft to 0.98 calibers forward of the base.

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LIST OF SYMBOLS

C_{D_B}	Base drag coefficient based on integration of pressure distributions over the total base area excluding the sustainer nozzle exit area and referenced to the total base area
C_T	Thrust coefficient = Thrust/q_∞ x Reference Area
d_n	Sustainer nozzle exit diameter
D_B	Body base diameter
M	Mach number
$\dot{m}_b$	Bleed mass flow
$\dot{m}_j$	Sustainer nozzle mass flow
$\dot{m}_\infty$	Body stream-tube mass flow
p	Local static pressure
p_b	Average base pressure, integrated over total base area excluding sustainer nozzle exit area
p_c	Sustainer nozzle chamber pressure
p_j	Sustainer nozzle exit static pressure
p_∞	Free-stream static pressure
q_∞	Free-stream dynamic pressure
V	Velocity
X	Distance from base of model
X_n	Distance from base of model to base of sustainer nozzle (Forward is positive.)

I. INTRODUCTION

Several potential applications exist in land combat and air defense weapons systems for boost-sustain propulsion. One of the advantages for this type of propulsion lies in the increase in missile performance arising from energy management considerations. As a part of the overall problem, it is necessary to investigate techniques for minimizing missile base drag. Current methods allow prediction and optimization of body forebody and friction drag with a reasonable degree of accuracy; however, methods are not available for reliably predicting the base drag of a body with an operating jet. The jet-on base drag of a body can be as high as 50 percent of the total drag; therefore techniques for predicting the jet-on base drag are needed for proper design and evaluation of the aerodynamic-propulsion configuration of missiles during sustainer operation.

This report presents the results of the second phase of a study on base drag reduction conducted as a part of SR Project, Base Drag Reduction, Code 5210.11.148. A body with concentric boost and sustainer rocket nozzles has been studied to determine the effects of base bleed, and the effects of sustainer nozzle diameter and position on the body base drag. The results of the first phase of the study have been presented in Reference 1.

The data presented in this report are based on the results of wind tunnel tests at Mach numbers 2.0 and 2.5. Parameters varied during the tests were Mach number, base bleed, nozzle diameter, nozzle position, and sustainer nozzle chamber pressure. The boost nozzle was inactive and the sustainer jet was simulated with air. The configuration tested was a body of revolution with an ogive nose and a cylindrical afterbody.

II. APPARATUS AND PROCEDURE

The test was conducted in Tunnel No. 1 of the Ballistic Research Laboratories, Aberdeen Proving Grounds, Maryland. That facility is a continuous flow, supersonic wind tunnel capable of operating at Mach numbers from 1.2 to 5.0, and has a test section 13 inches wide by 15 inches high.

The model tested was a body of revolution with a 4-caliber, tangent ogive nose, and a 2-caliber cylindrical afterbody. It was mounted from the tunnel ceiling at 0° angle of attack by a rigid strut containing the instrumentation and air supply lines. A sustainer rocket nozzle, concentric to a boost rocket nozzle, could be tested at any of ten longitudinal positions between, -.60 and +.98 calibers from the base of the body. The sustainer nozzles had exit diameters of 0.10, 0.20, and 0.30 calibers and were designed for an exit Mach number of 2.7 ($p_j/p_c = 0.0427$). The sustainer jet was simulated with dry air, and the boost nozzle was inactive. During the bleed runs, air was bled from the sustainer chamber to the boost nozzle chamber through orifices in the sustainer nozzle chamber wall. The amount of bleed air was varied by varying the size and number of bleed orifices. Figure 1 presents sketches of the model installation and geometry.

The base of the model was instrumented with pressure orifices along the body just forward of the base, on the base annulus, and along the interior of the boost nozzle as shown in Figure 1. Pressures at the orifices were measured with pressure transducers. Sustainer air supply pressure (p_c) was measured at an orifice in the settling chamber upstream of the nozzle throat.

During each run the sustainer supply pressure was varied while holding constant the test section Mach number, test section static pressure, sustainer nozzle position, and ratio of bleed to sustainer jet mass flow. Data recorded were test section stagnation pressure and temperature, sustainer air supply pressure, model orifice pressures, and transducer reference pressure. Accuracies of the data obtained are the following:

Mach number	±.002
Local model pressures	±.0125 psi
Sustainer supply pressure	
0 - 15 psi range	±.030 psi
0 - 100 psi range	±.200 psi
0 - 320 psi range	±.600 psi

The model local pressures were reduced to pressure coefficient and pressure ratio form, and the base drag coefficients were computed by integrating the base pressure distributions where:

$$C_{D_B} = \frac{1}{S_B} \sum a_i C_{p_i}$$

and S_B = Total base area

a_i = Incremental area

C_{p_i} = Local pressure coefficient

A more detailed discussion of the test apparatus and test procedure as well as the basic data from the test is presented in Reference 2.

III. RESULTS

The wind tunnel test results from Reference 2 have been analyzed to determine the effects of the various test parameters on base drag. The analysis is limited to values of sustainer chamber pressures sufficient to completely fill the sustainer nozzle. Although the test configuration has an inactive boost rocket nozzle concentric to an active sustainer rocket nozzle, or in effect an open base, the data are comparable to data for closed base configurations except for conditions where the sustainer jet impinged on the boost nozzle wall. Subsequent references to the nozzle and jet will refer to the sustainer nozzle and jet.

Figures 2 through 5 present the basic test results and show the effects of sustainer nozzle diameter and position and the effects of base bleed on base drag as a function of jet chamber to free-stream static pressure ratio. These data exhibit a characteristic variation of base drag with jet pressure ratio which is discussed in detail and related to base wake flow in Reference 3.

A. Effect of Diameter Ratio and Mach Number

Analysis of the data for the configuration with the nozzle at the model base ($X_n/D_B = 0.0$) shows a dependence of base pressure on thrust level and jet momentum ratio which are related. Figure 6 presents base pressure ratio as a function of thrust coefficient and Figure 7 presents base pressure ratio as a function of jet momentum ratio for nozzle diameter ratios of 0.10, 0.20, and 0.30 at Mach numbers of 2.0 and 2.5. These data indicate that base pressure ratio is independent of nozzle diameter, jet pressure ratio, and free-stream conditions except for their relative inputs to the thrust coefficient or momentum ratio. Reference 1 presents data from the first series of tests of the model at Mach numbers of 2.0, 2.5, 3.0, and 3.5 for a nozzle diameter ratio of 0.24. Due to instrumentation difficulties, the accuracy of the data from Reference 1 does not approach the accuracy of the present data; however, the data are useful to indicate trends and are presented in Figure 8 as a function of thrust coefficient to illustrate the independence of jet-on base pressure on free-stream Mach number except for its input to thrust coefficient. The relationship between jet-on base pressure and thrust coefficient and momentum ratio correlates well with experimental data from sources for bodies with supersonic jets.

B. Effect of Base Bleed

Air was bled into the boost nozzle combustion chamber through orifices in the sustainer nozzle combustion chamber wall. In most cases, the bleed mass flow was sufficient to choke the boost nozzle throat. Figure 9 presents boost nozzle pressure distributions for various bleed ratios with the 0.20 diameter ratio sustainer nozzle. These data illustrate that the boost nozzle was choked for all bleed ratios except the .015 with the 0.20 diameter ratio nozzle, and provide data for convenient determination of the actual ratio of bleed mass flow to sustainer mass flow for conditions where the boost nozzle was choked. Figure 10 presents calculated values of bleed mass flow ratios based on the pressure distributions of Figure 9. For values of bleed mass flow not sufficient to choke the boost nozzle throat, nominal values are given based on orifice area ratios.

Bleeding gases into the base area increases the base pressure as a function of the bleed mass. The incremental increase in base pressure ratio due to base bleed is presented in Figure 11 as a function of the ratio of bleed mass flow to body stream-tube mass flow. The apparent Mach number effect can be removed by dividing the mass flow ratio by the free-stream velocity. Since the bleed velocity is believed to be constant, the dependence of the effect of base bleed on base pressure ratio on bleed momentum ratio is indicated. The bleed velocity at the base could not be determined from the available data, therefore the bleed momentum ratio could not be calculated. However, since the base pressure ratio without base bleed is a function of jet momentum ratio, it is not illogical to believe that the effects of base bleed are also a function of bleed momentum ratio. The boost nozzle produces some thrust due to bleed, however the effects on base pressure are far greater than the effects of bleed thrust alone.

C. Effect of Longitudinal Position

Extension of the sustainer nozzle aft of the base of the body induces an incremental increase in base pressure which varies almost linearly with nozzle position but which does not vary with nozzle diameter of jet pressure ratio. An effect of free-stream Mach number is also indicated; however, sufficient data are not available to determine the Mach number effects. Figure 12 presents the incremental increase in base pressure ratio as a function of aft nozzle position. It is anticipated that the base pressure would continue to increase with aft nozzle position until the sustainer nozzle approached the position of the jet-off trailing shock ($X_n/D_B \approx -1.20$). Since the aft nozzle positions induce an increase in base pressure which is independent of nozzle diameter and jet pressure ratio, the base pressure cannot be correlated on a momentum ratio or a thrust coefficient basis.

Movement of the sustainer nozzle forward into the base cavity induces a corresponding decrease in base pressure until a position is reached where the sustainer jet inpinges on the boost nozzle. With jet impingement, the static pressure on the boost nozzle aft of impingement is increased due to a pressure rise across an oblique shock produced by impingement. Further movement of the sustainer into the base cavity increases the area of the boost nozzle affected and also increases the angle of impingement which in turn causes an increase in pressure rise across the oblique shock. Therefore movement of the sustainer nozzle forward after the jet has impinged causes an increase in base pressure. This effect is discussed in more detail in Reference 1. It is interesting to note that after the jet has impinged on the boost nozzle base pressure again becomes a function of momentum ratio and thrust coefficient.

Figure 13 illustrates the incremental change in base pressure ratio with nozzle position for the 0.20 d_n/D_B nozzle at $M = 2.5$ for several jet pressure ratios.

Reference 1 illustrated that, for a given nozzle position, the point of jet impingement was independent of jet pressure ratio and external conditions. Figure 14 also illustrates that the point of jet impingement is independent of nozzle diameter.

IV. CONCLUSIONS

The following conclusions can be made, based on analysis of the test data:

1. The base pressure ratio, for bodies with jets coplaner to the base, can be expressed as a function of either jet momentum ratio or thrust coefficient and is independent of nozzle diameter, jet pressure ratio, and free-stream conditions except for their respective inputs to the momentum ratio and thrust coefficient.

2. The increase in base pressure due to gases bled into the base area can be expressed as a function of the bleed mass momentum ratio and is independent of bleed area or free-stream conditions except for their respective inputs to the momentum ratio.

3. Extending the nozzle aft of the body base causes an increase in base pressure which is a function of the amount of extension and free-stream Mach number but is independent of nozzle diameter and jet pressure ratio.

4. Moving the nozzle forward into the body can increase the base pressure due to impingement of the jet on the body internal surfaces. The amount is a function of jet conditions and geometry but is independent of environmental conditions.

It is recommended that future phases of the base drag reduction study be conducted to determine the effects on jet-on base drag of the following:

1. Effects of base bleed over wide Mach number range.

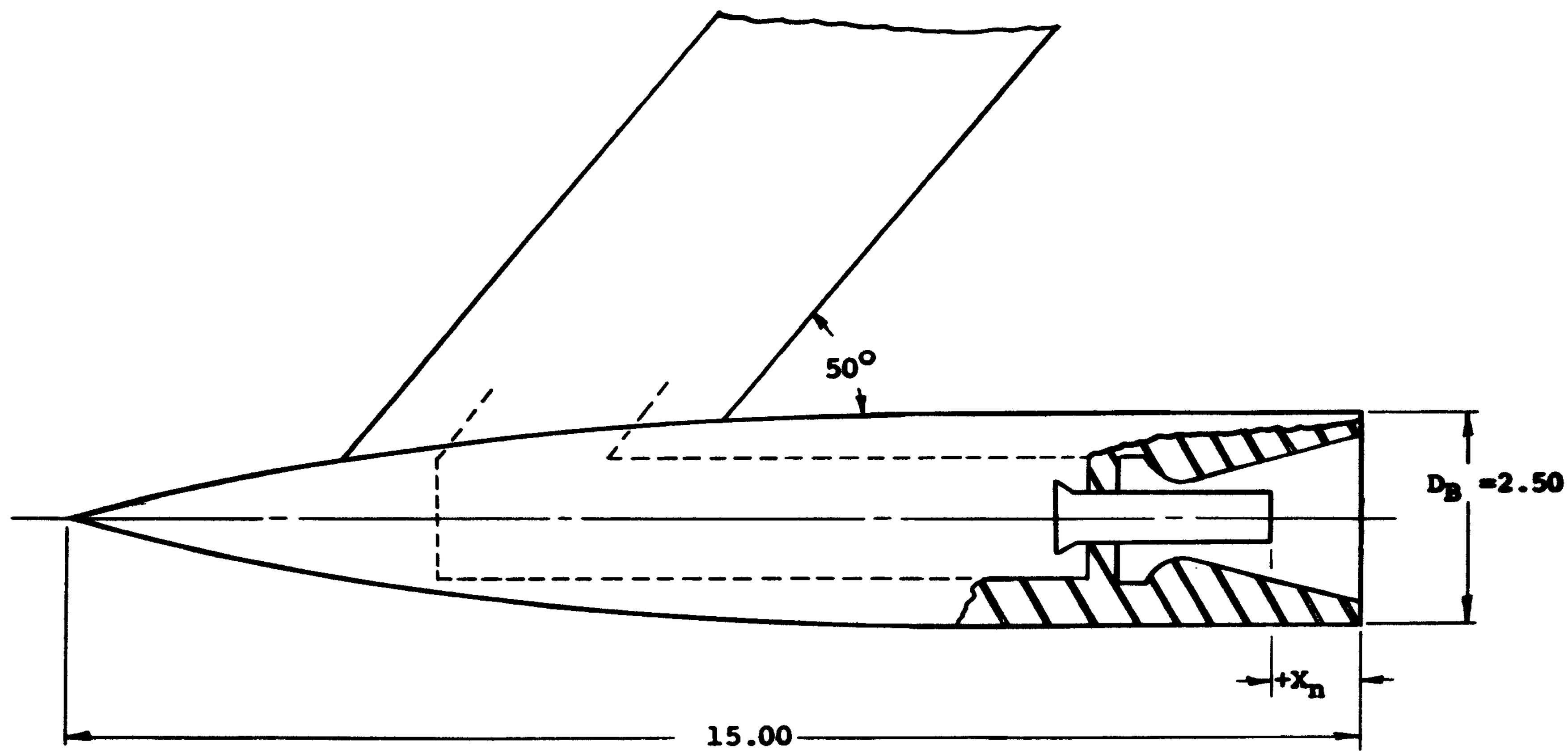
2. Effects of aft nozzle extensions over wide Mach number range and for further aft extensions.

3. Effects of jet Mach number and expansion angle.

4. Effects of jet temperature and physical composition.

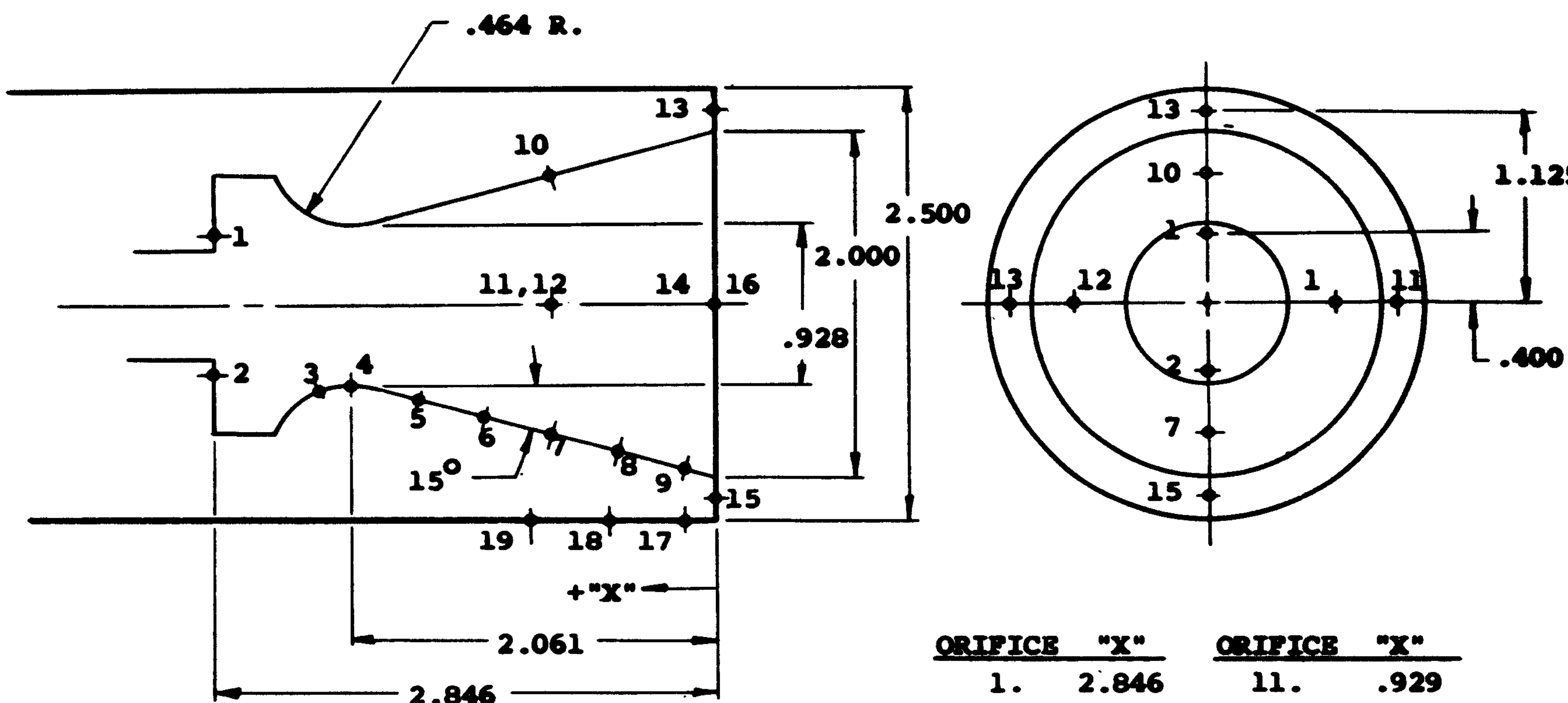
5. Effects of afterbody geometry.

6. Potential heating problems associated with flow impingement on the boost nozzle.



a. Model Installation

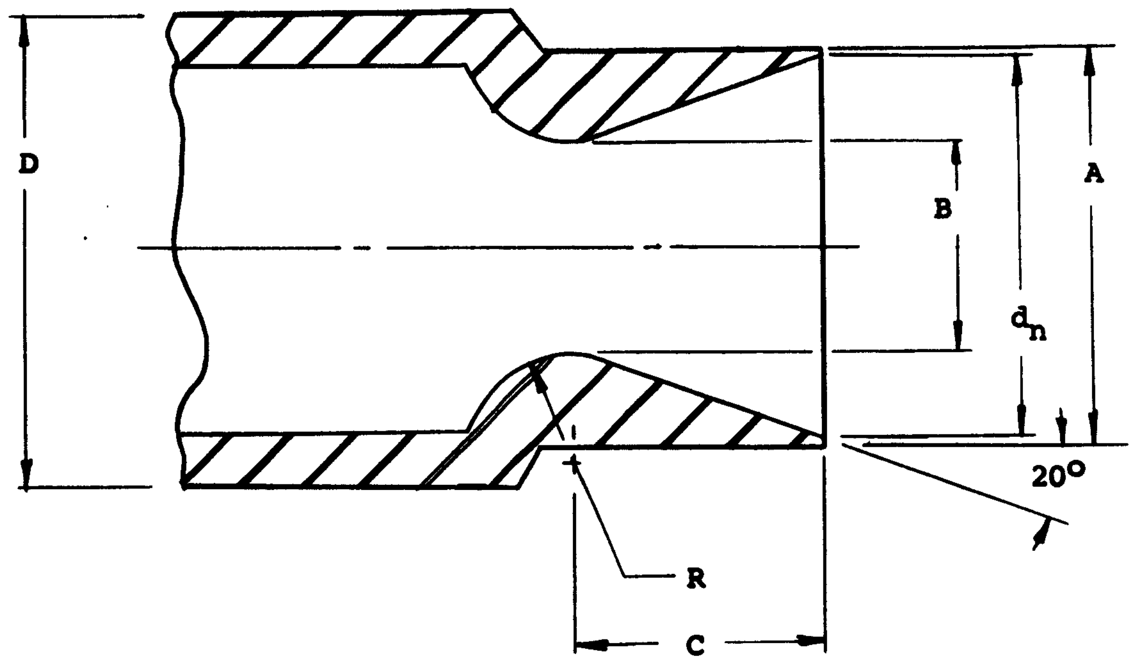
Figure 1. Model Details



ORIFICE	"X"	ORIFICE	"X"
1.	2.846	11.	.929
2.	2.846	12.	.929
3.	2.398	13.	.000
4.	2.061	14.	.000
5.	1.685	15.	.000
6.	1.307	16.	.000
7.	.929	17.	.180
8.	.552	18.	1.060
9.	.174	19.	2.060
10.	.929		

b. Boost Nozzle Geometry

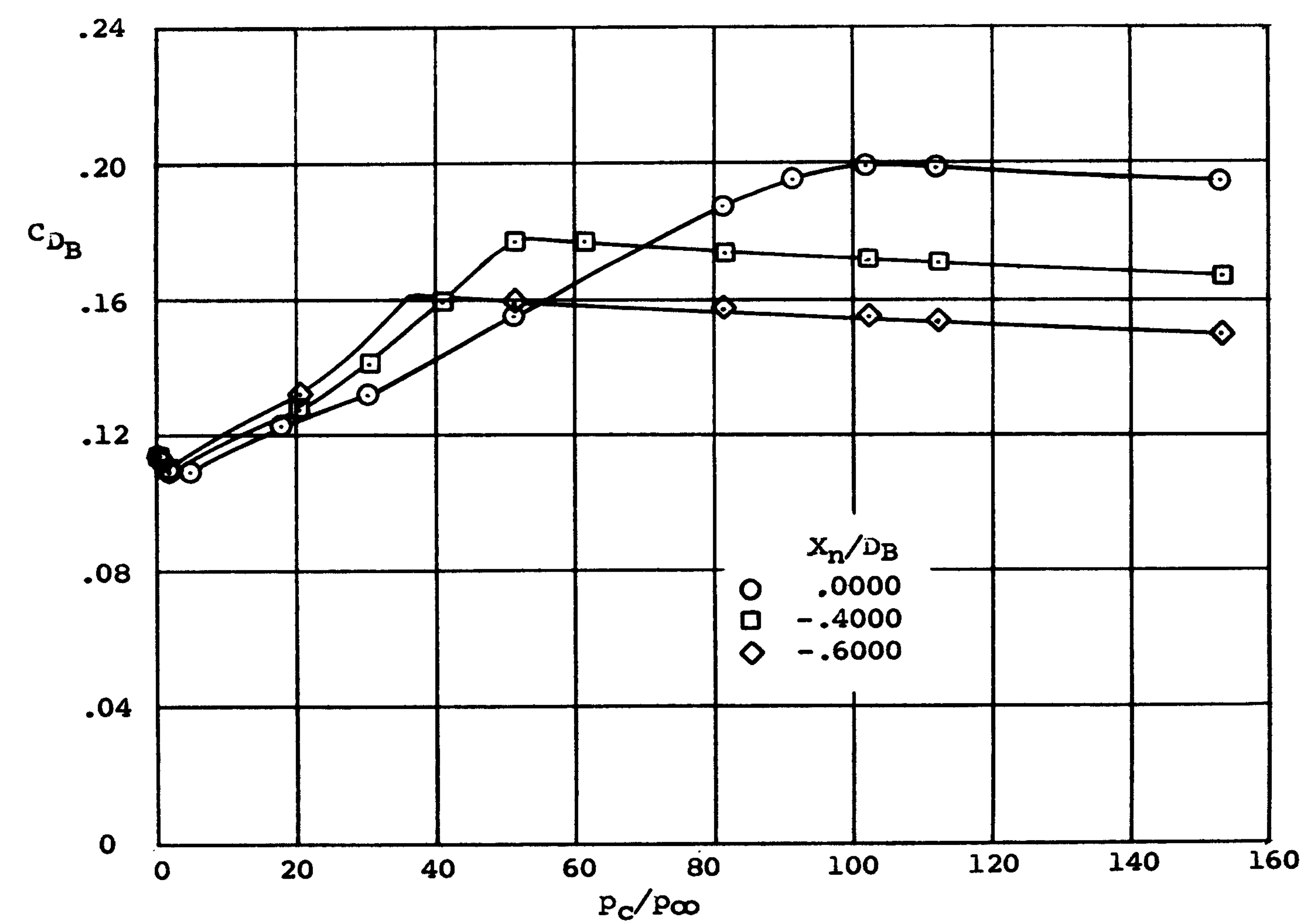
Figure 1. Continued



d_n/D_B	d_n	A	B	C	D	R
0.10	0.250	0.27	0.140	0.163	0.623	0.070
0.20	0.500	0.52	0.280	0.327	0.623	0.140
0.30	0.750	0.79	0.420	0.490	0.623	0.210

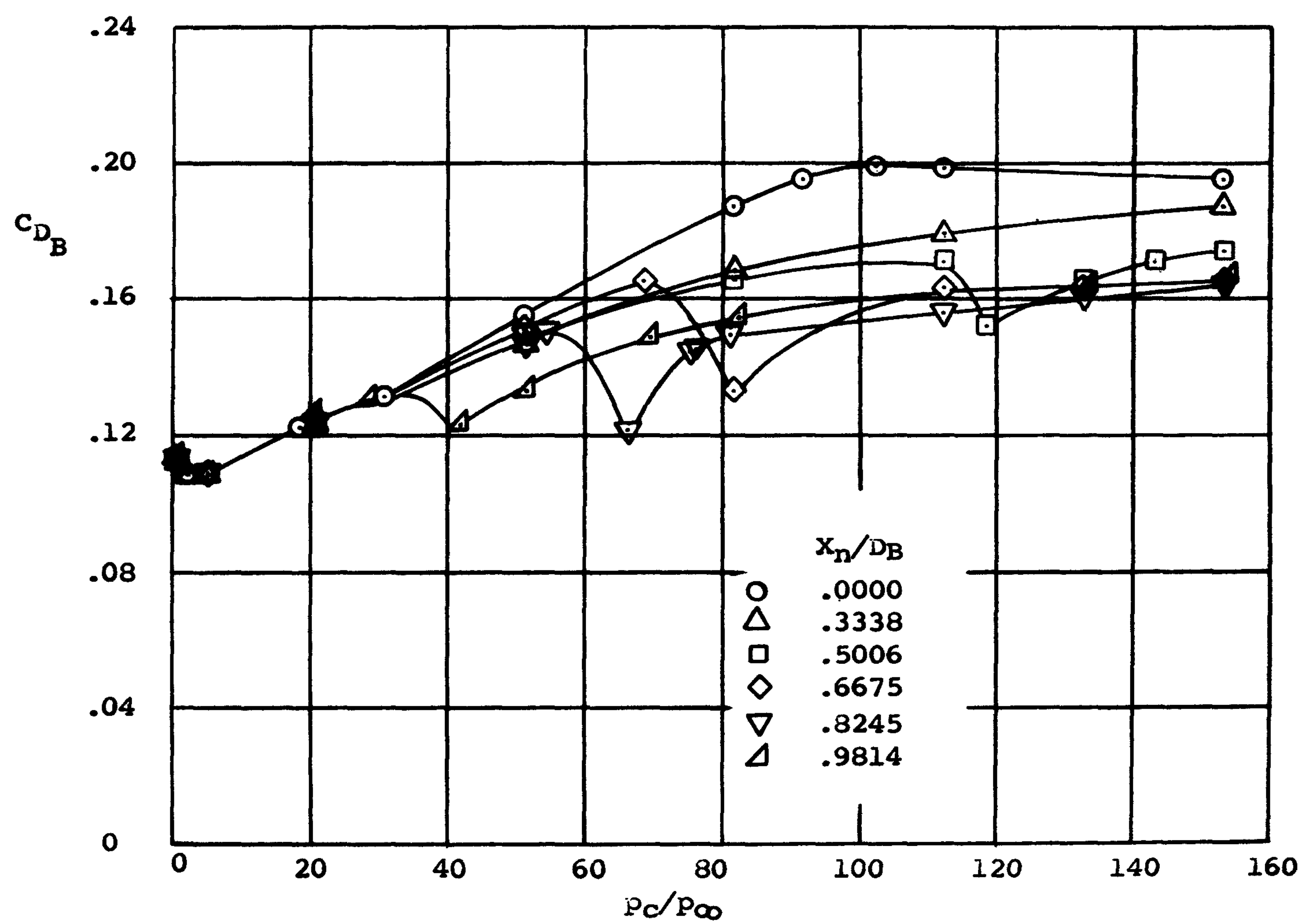
c. Sustainer Nozzle Geometry

Figure 1. Concluded



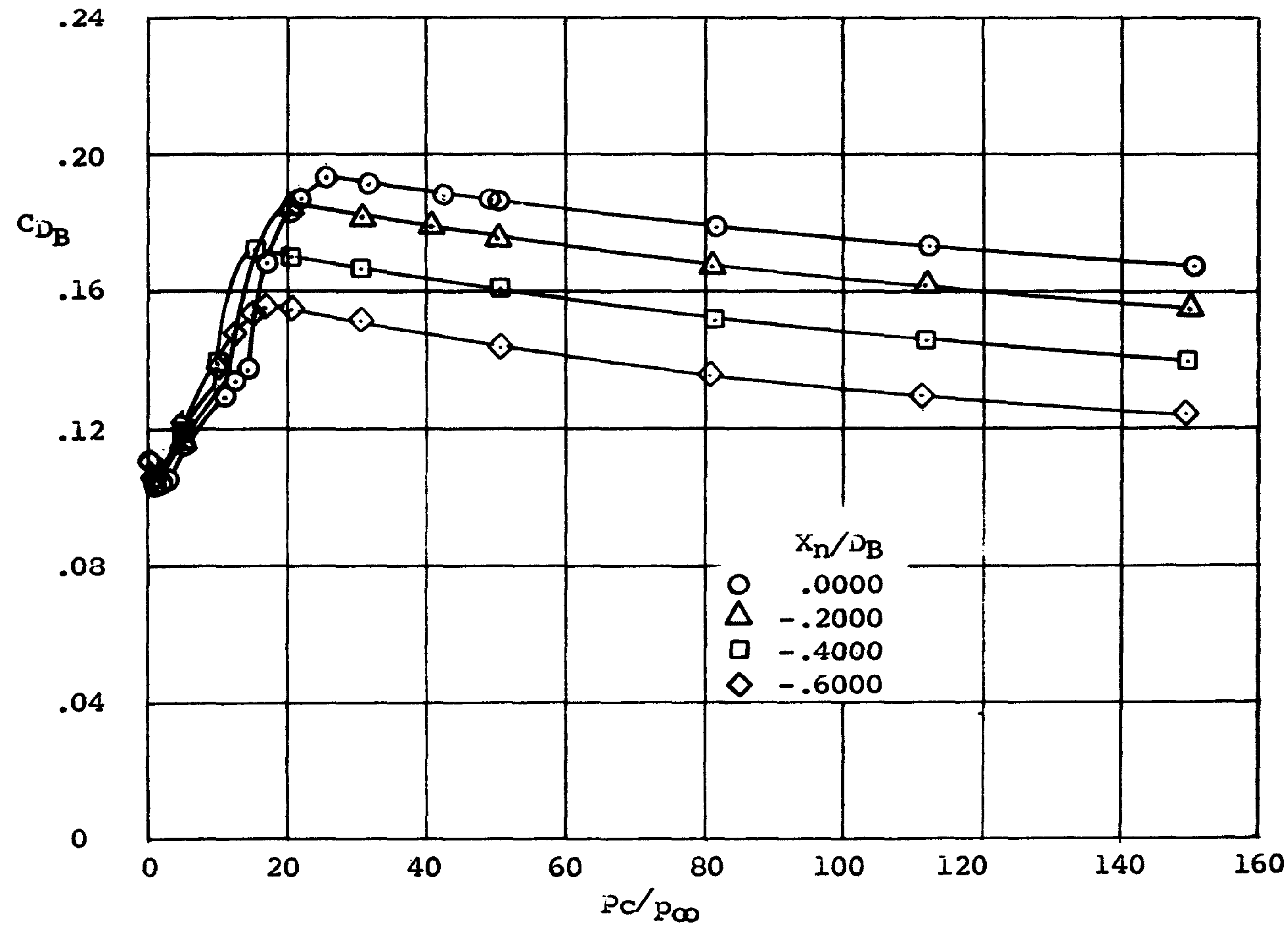
a. Aft Nozzle Positions

Figure 2. Effects of Sustainer Nozzle Position on Base Drag. $d_n/D_B = 0.10$; $M = 2.5$



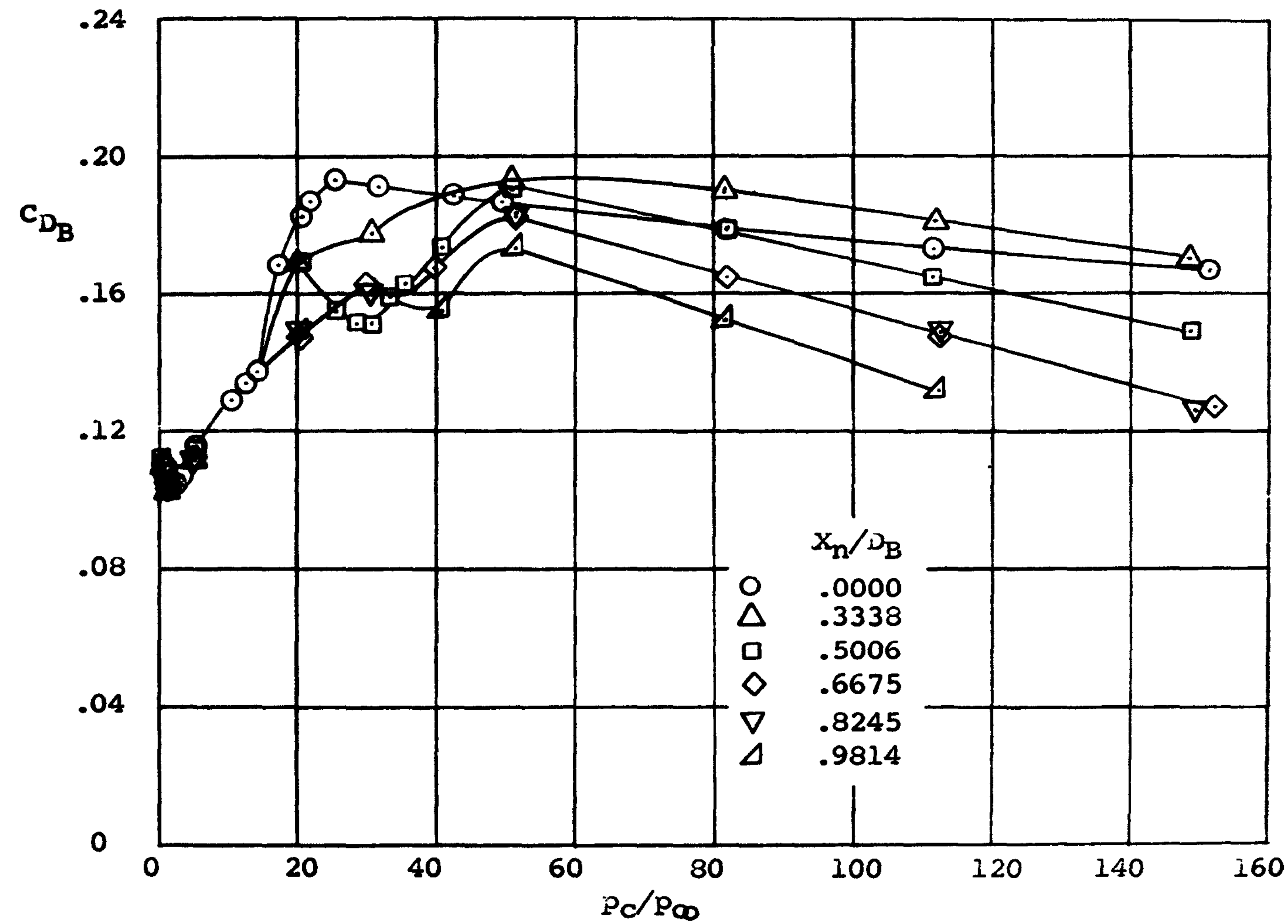
b. Forward Nozzle Positions

Figure 2. Continued



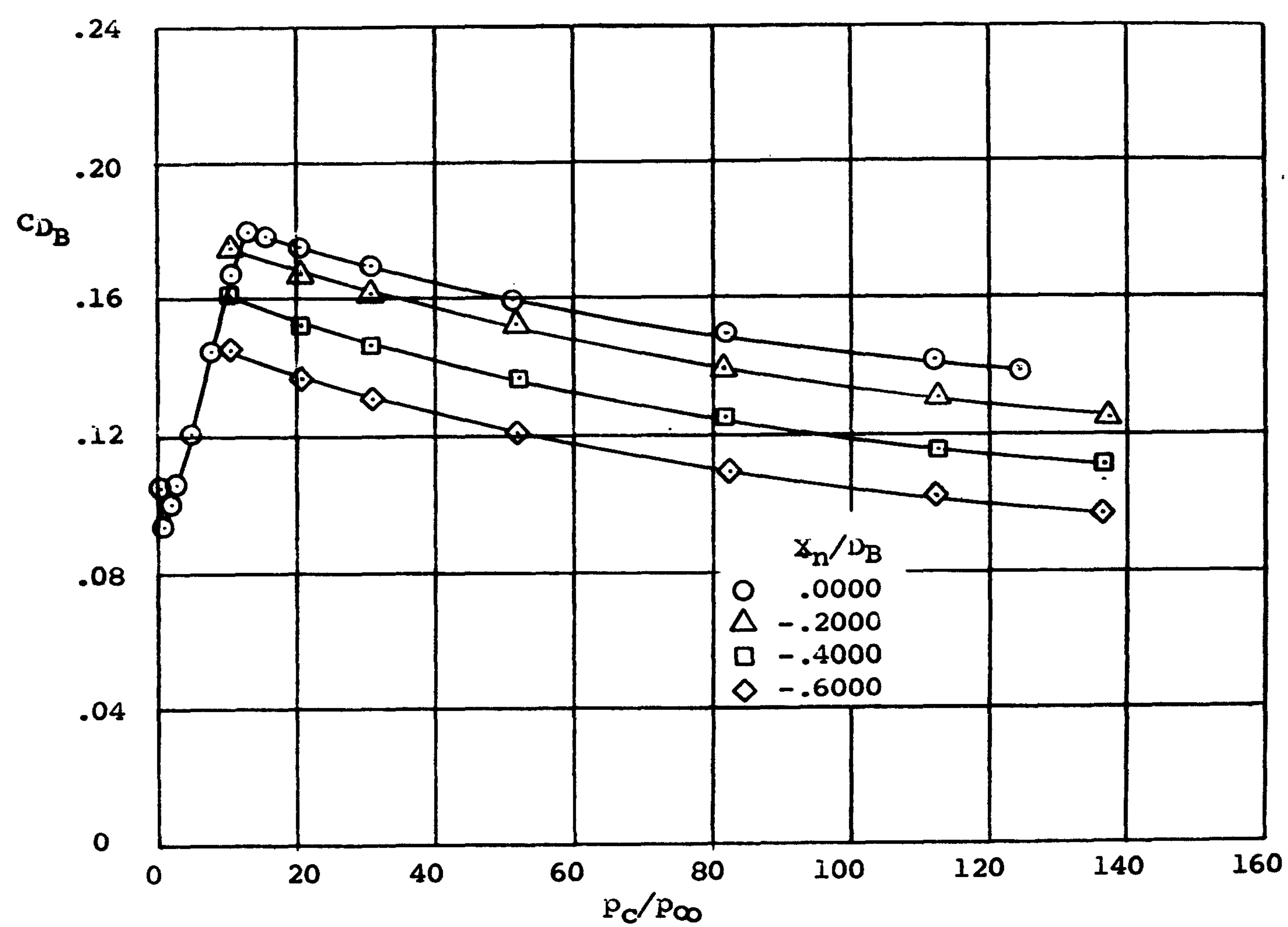
a. Aft Nozzle Positions

Figure 3. Effects of Sustainer Nozzle Position on Base Drag. $d_n/D_B = 0.20$; $M = 2.5$



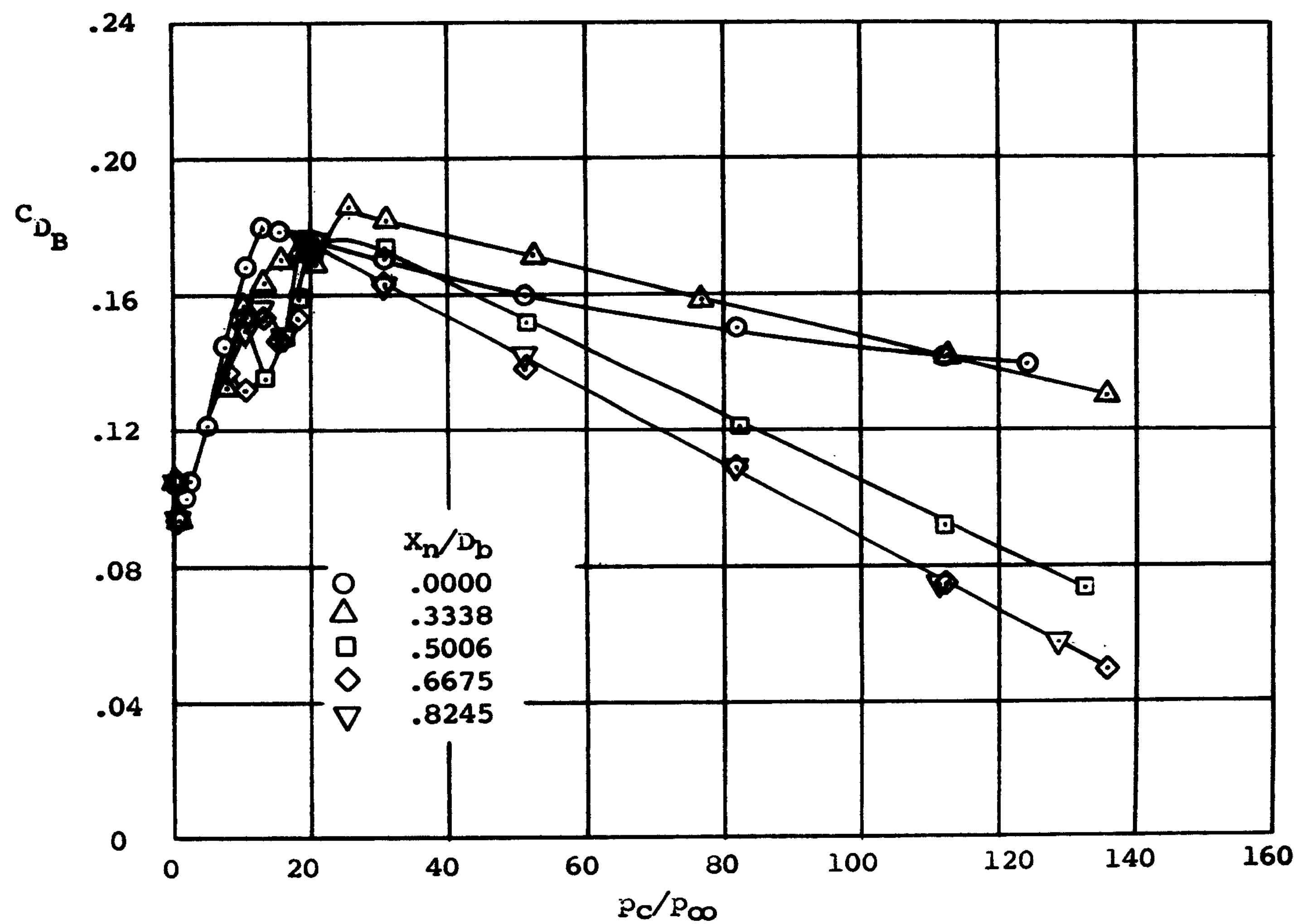
b. Forward Nozzle Positions

Figure 3. Continued



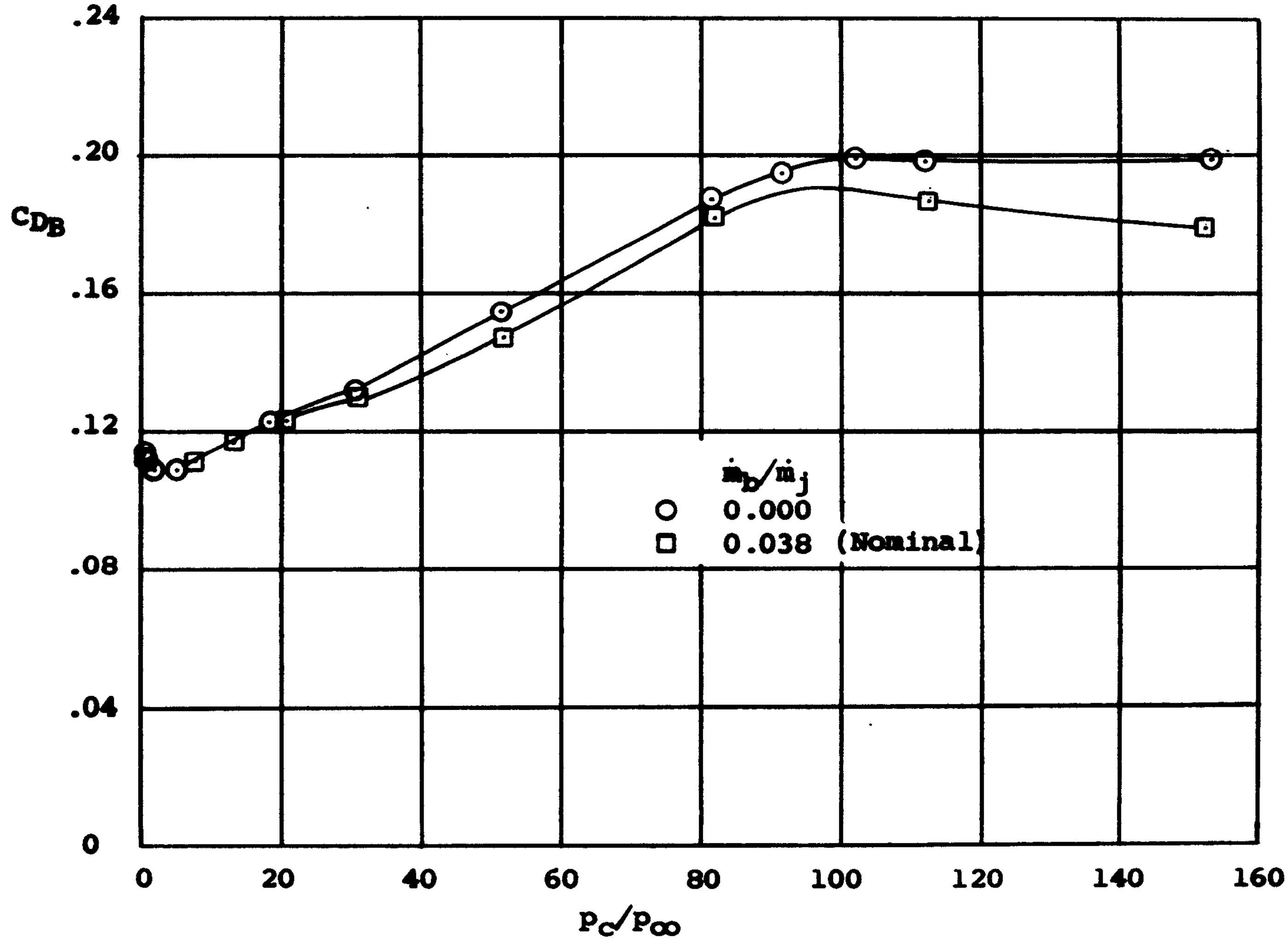
a. Aft Nozzle Positions

Figure 4. Effects of Sustainer Nozzle Position on Base Drag. $d_n/D_B = 0.30$; $M = 2.5$



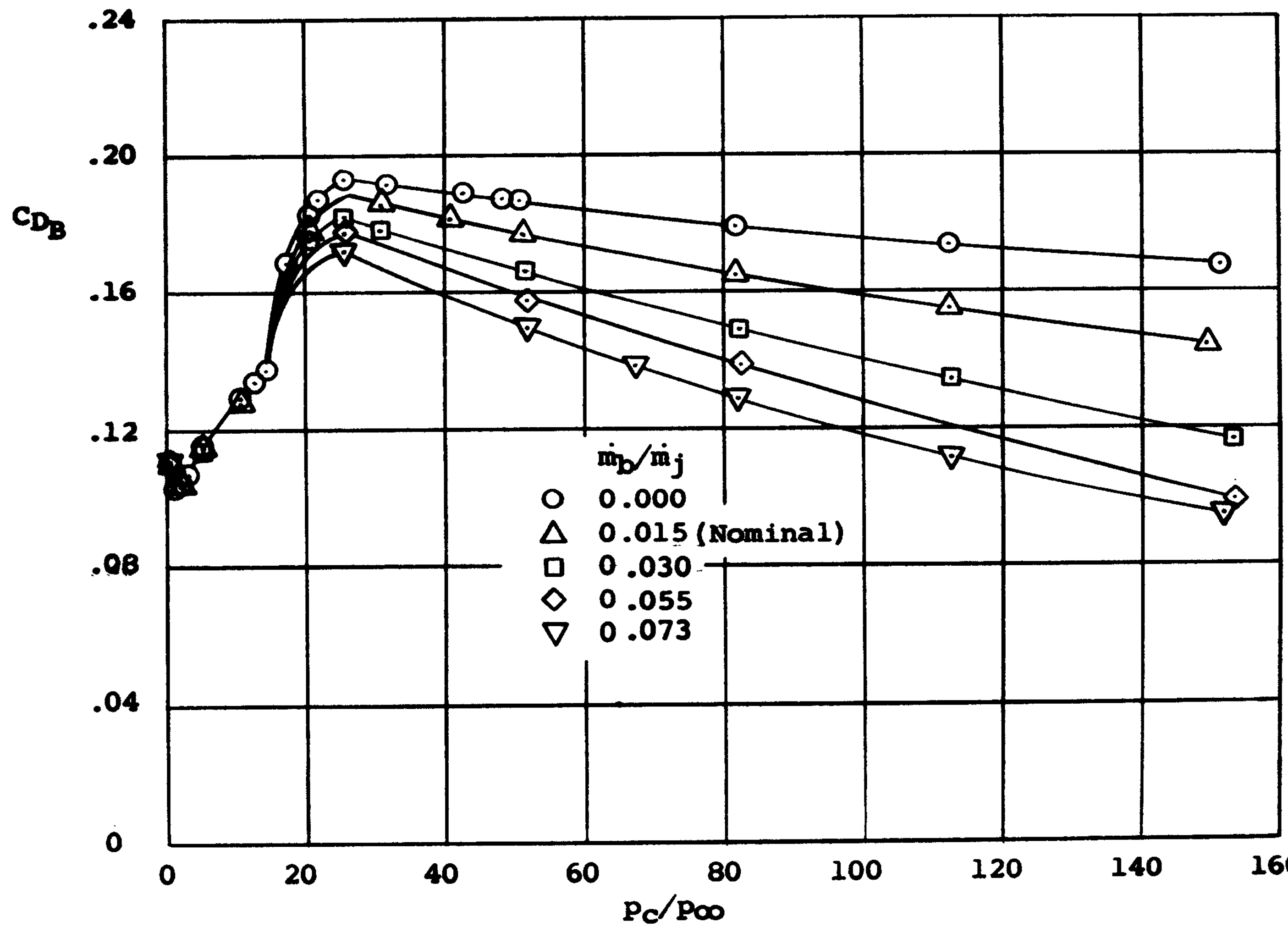
b. Forward Nozzle Positions

Figure 4. Continued



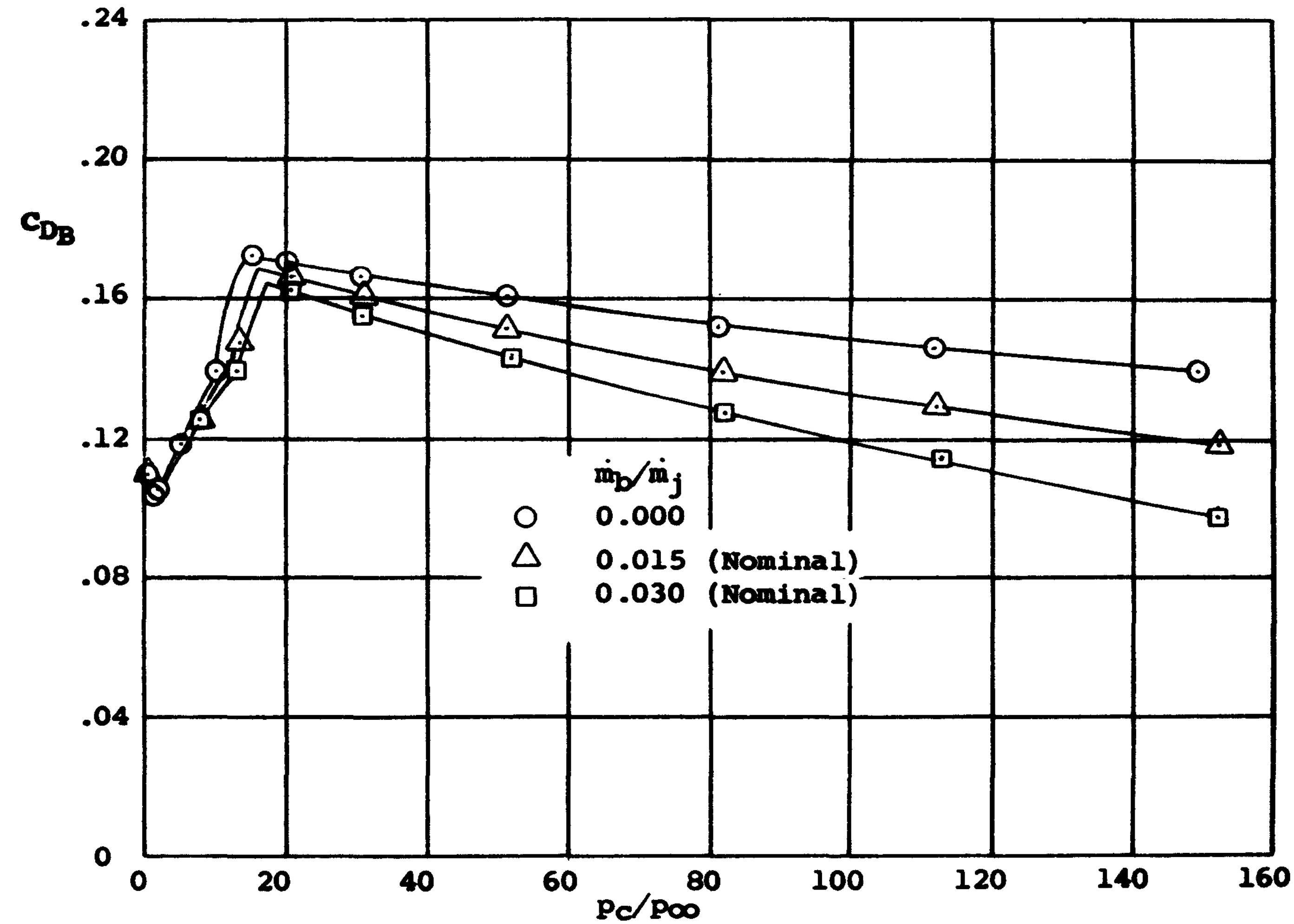
a. $d_n/D_B = 0.10$; $X_n/D_B = 0.0$

Figure 5. Effects of Base Bleed on Base Drag at $M = 2.5$



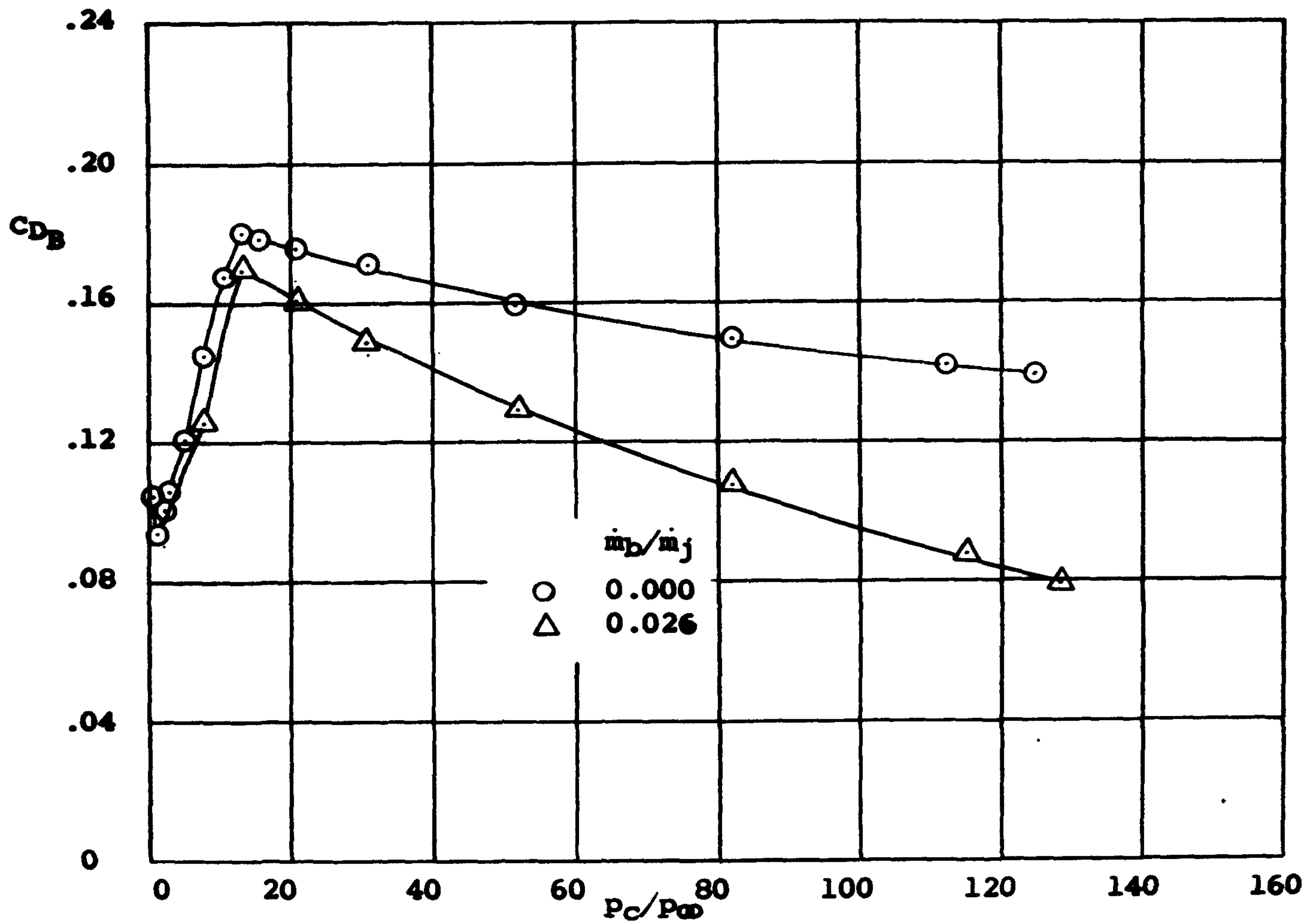
b. $d_n/D_B = 0.20$; $X_n/D_B = 0.0$

Figure 5. Continued



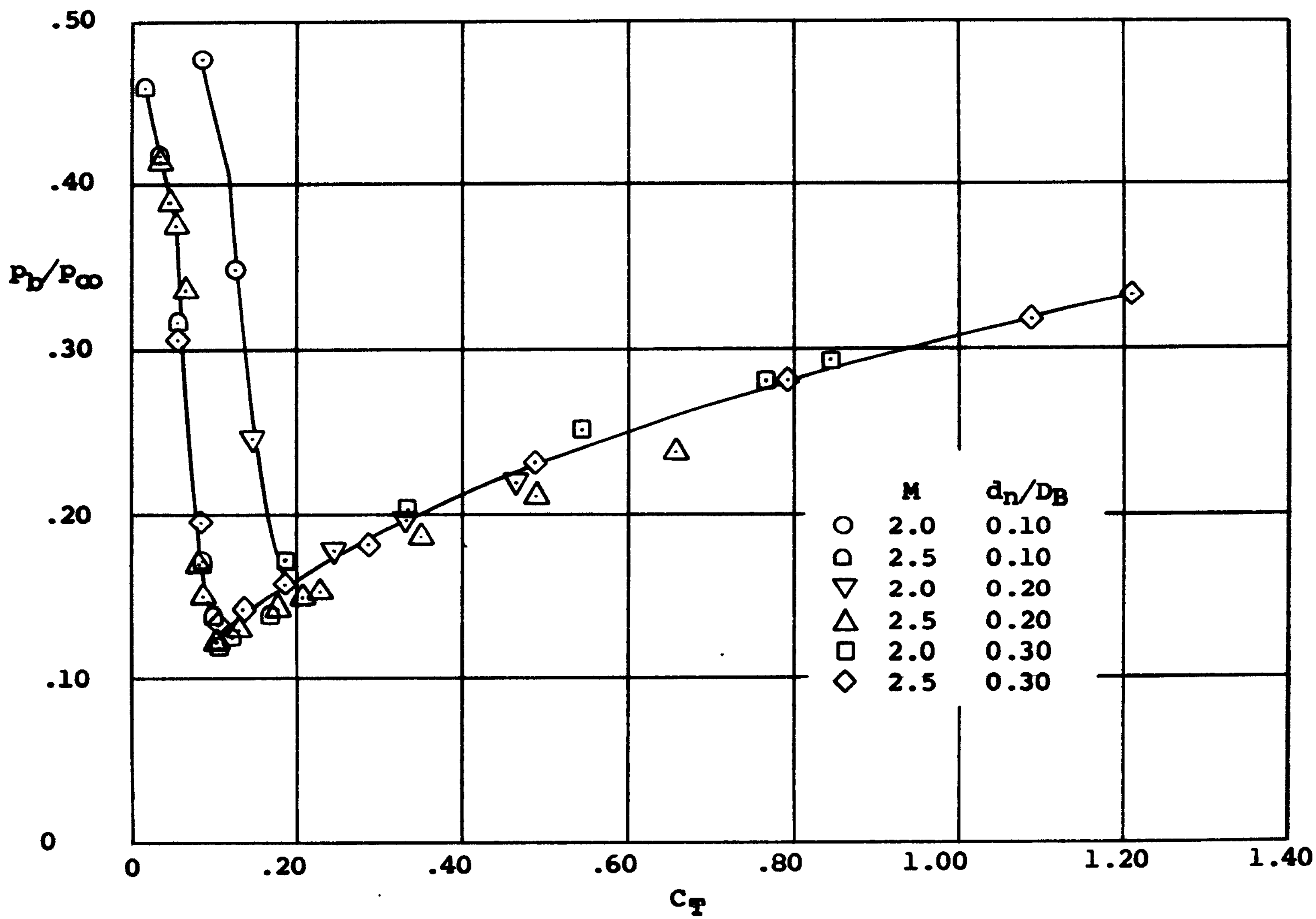
c. $d_n/D_B = 0.20$; $X_n/D_B = -0.40$

Figure 5. Continued



d. $d_n/D_B = 0.30$; $X_n/D_B = 0.00$

Figure 5. Continued



$X_n/D_B = 0.0$

Figure 6. Effects of Mach Number and Sustainer Nozzle Diameter Ratio on Base Pressure Ratio.

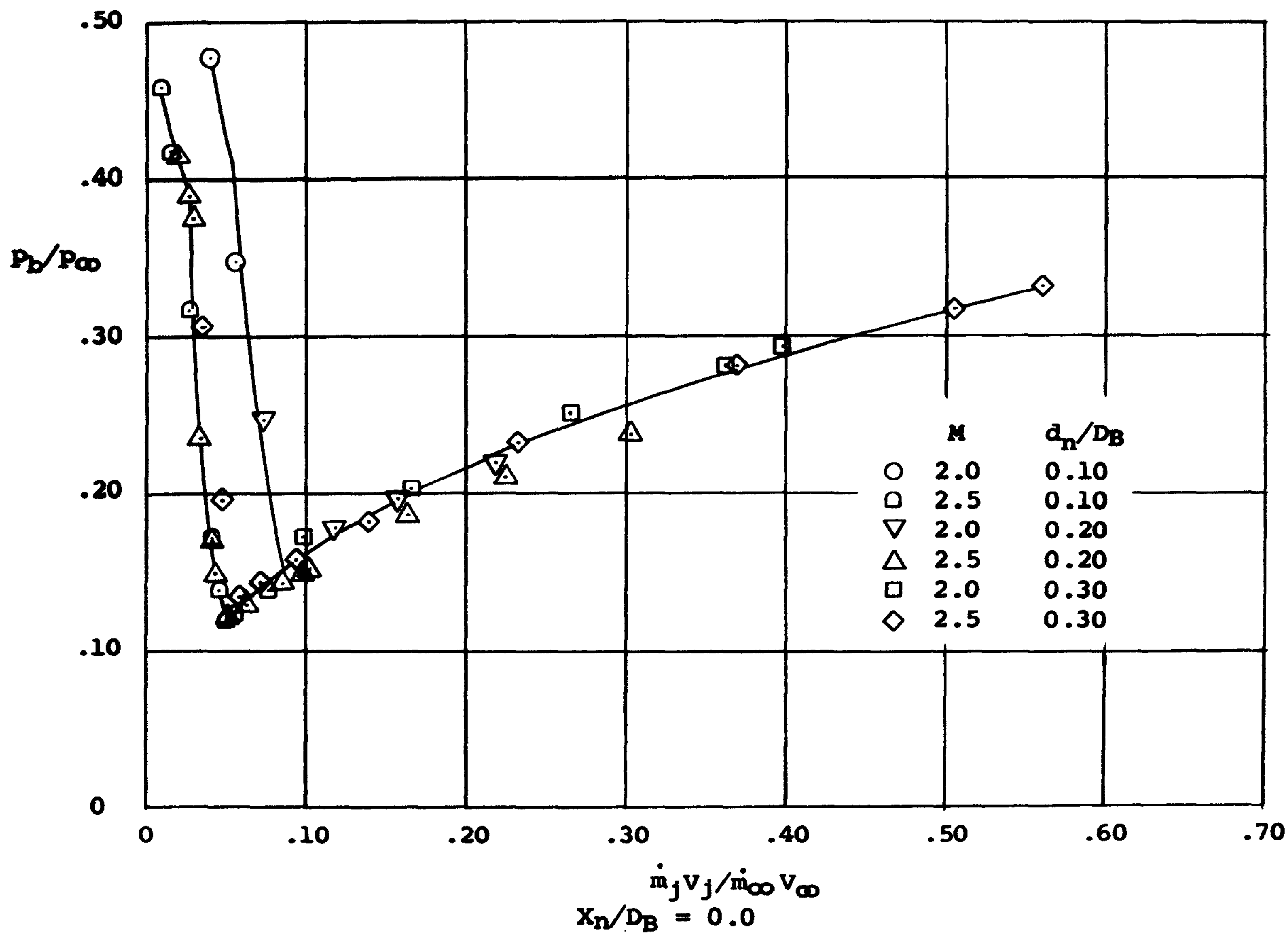
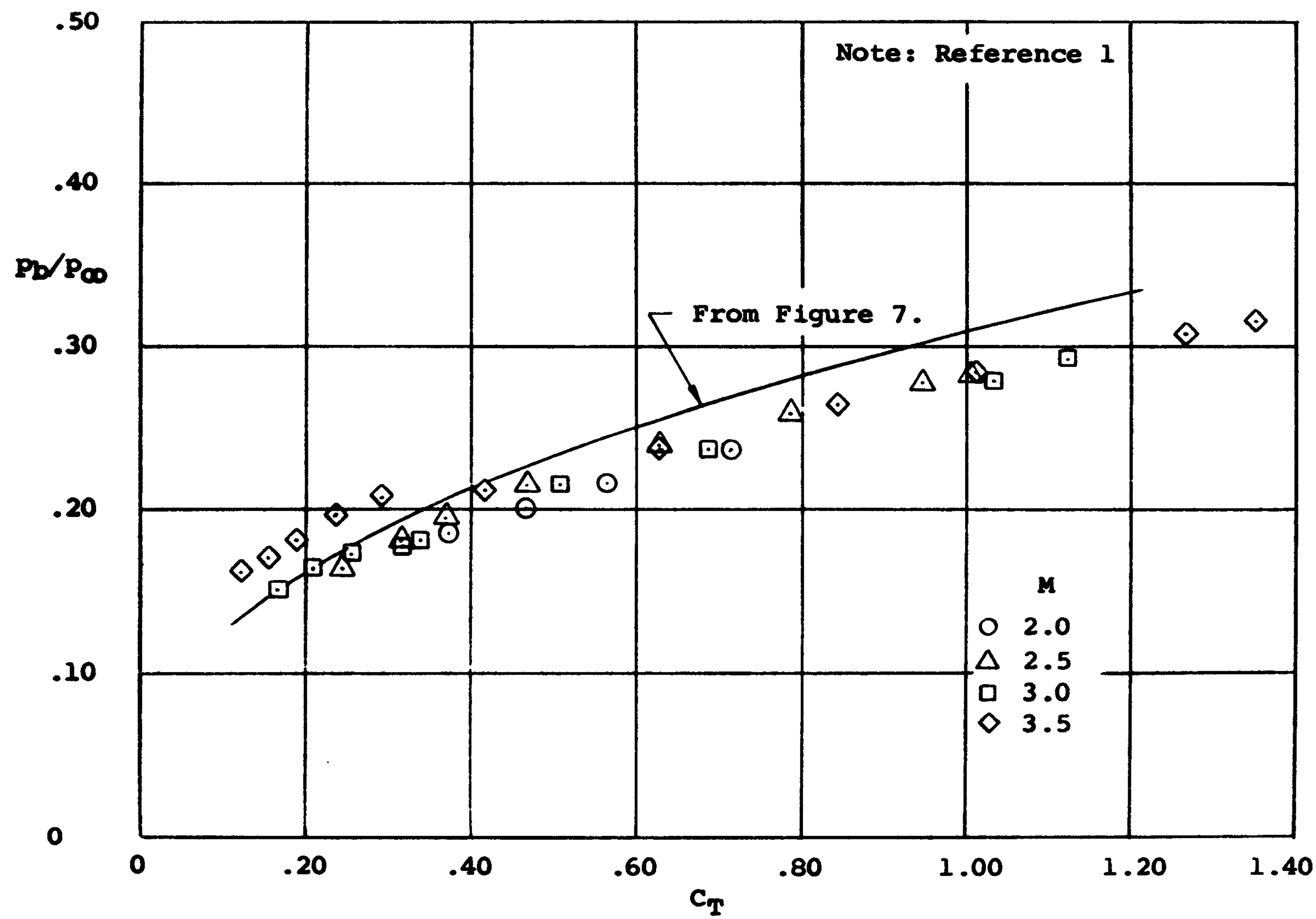


Figure 7. Effects of Mach Number and Sustainer Nozzle Diameter Ratio on Base Pressure Ratio.



$X_n/D_B = 0.0; \quad d_n/D_B = 0.24$

Figure 8. Effects of Mach Number on Base Pressure Ratio

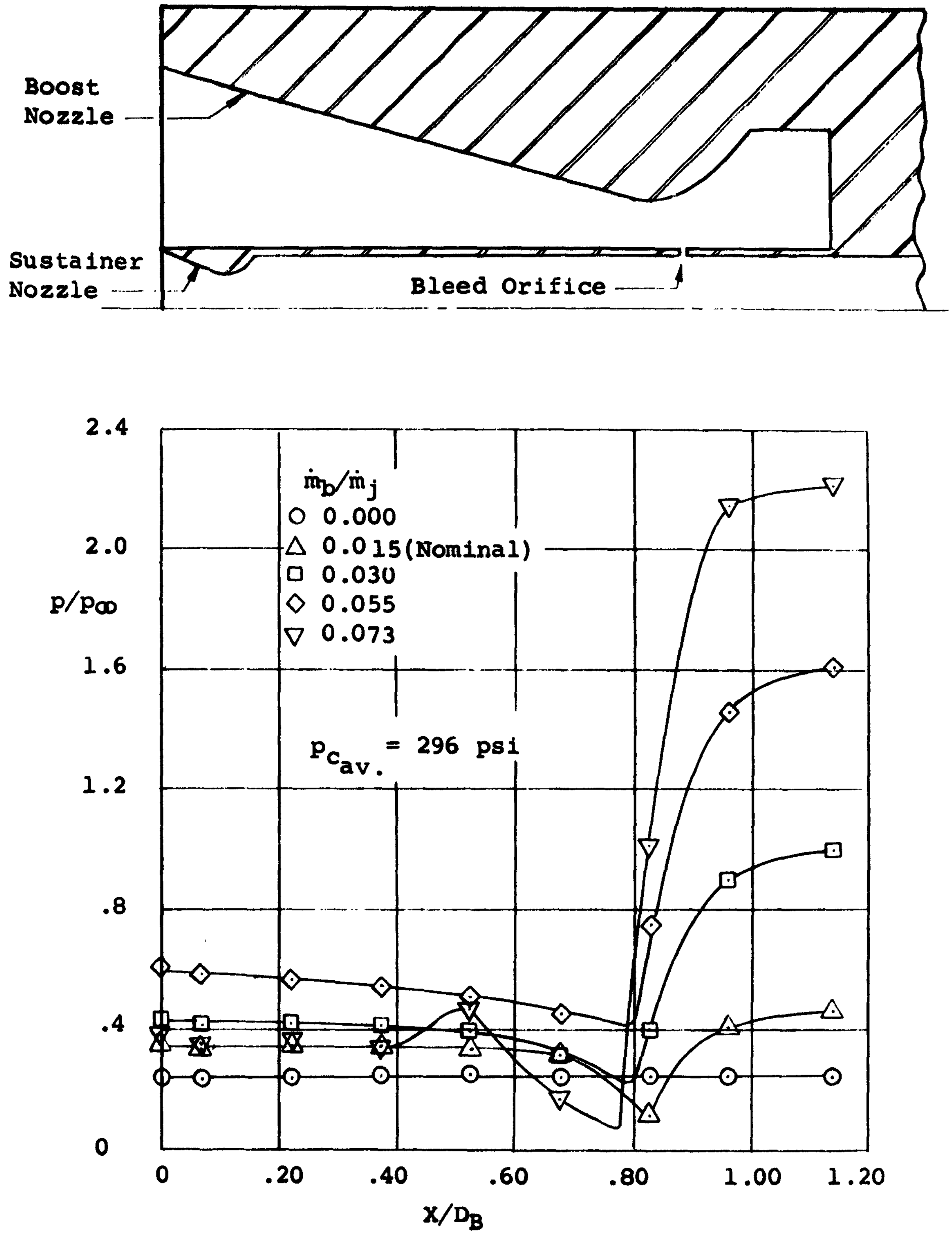


Figure 9. Effects of Bleed on Base Pressure Distribution.
$M = 2.5$; $d_n/D_B = .20$; $X_n/D_B = 0.00$

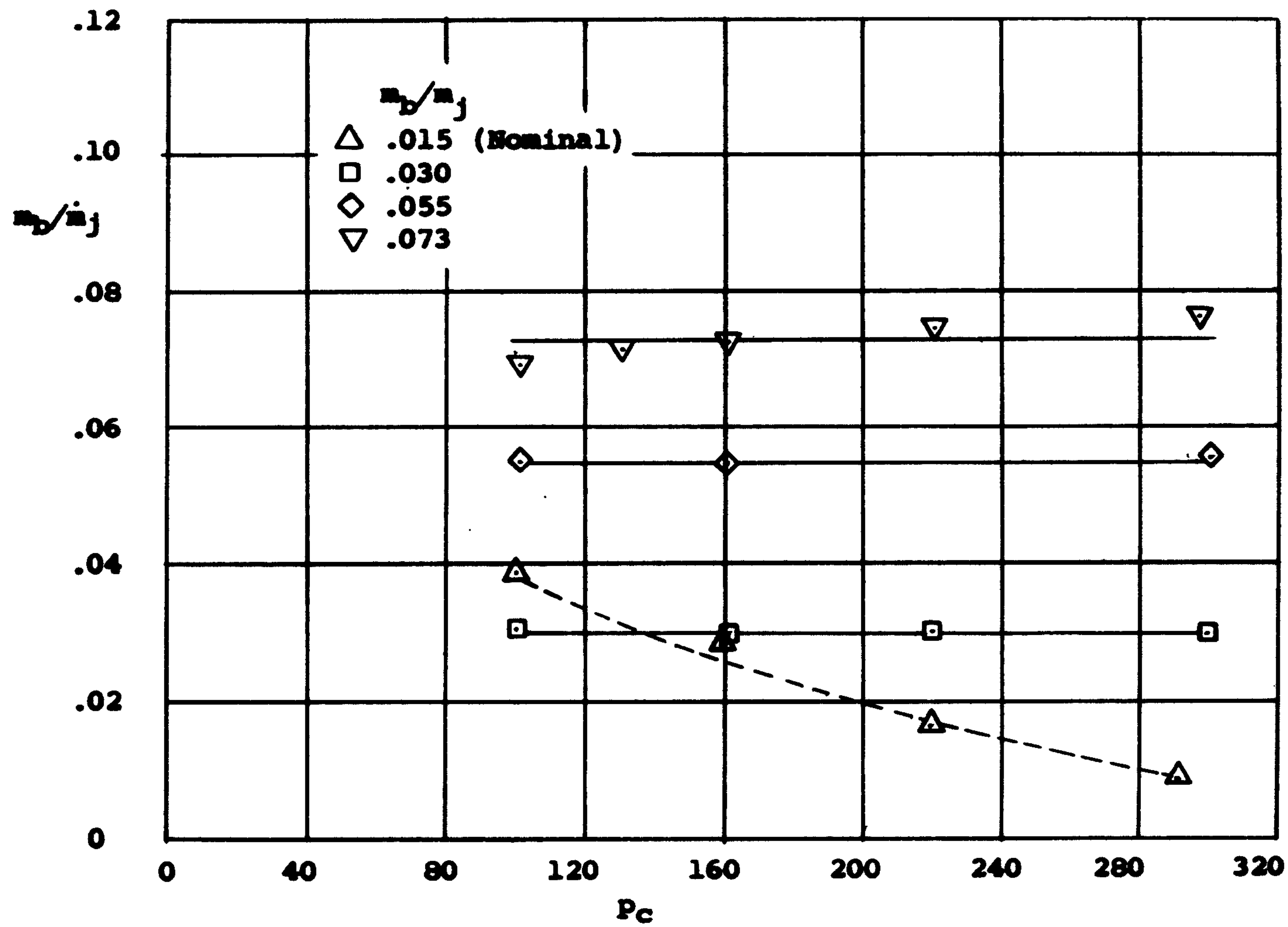


Figure 10. Variation in Bleed Mass Flow Ratio With Sustainer Jet Chamber Pressure $M = 2.5$; $d_n/D_B = .20$; $X_n/D_B = 0.00$

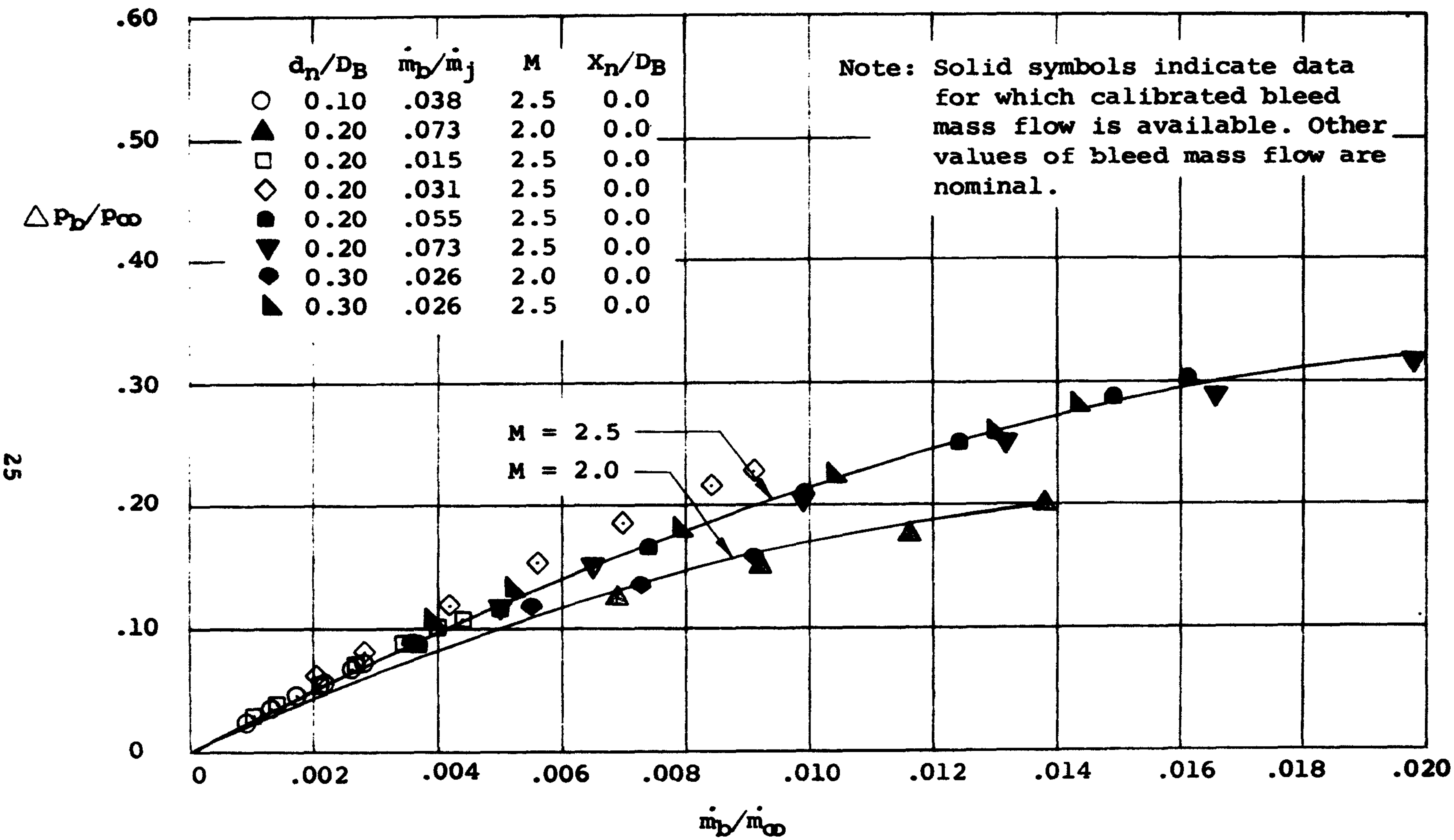


Figure 11. Increase in Base Pressure Ratio Due to Base Bleed.

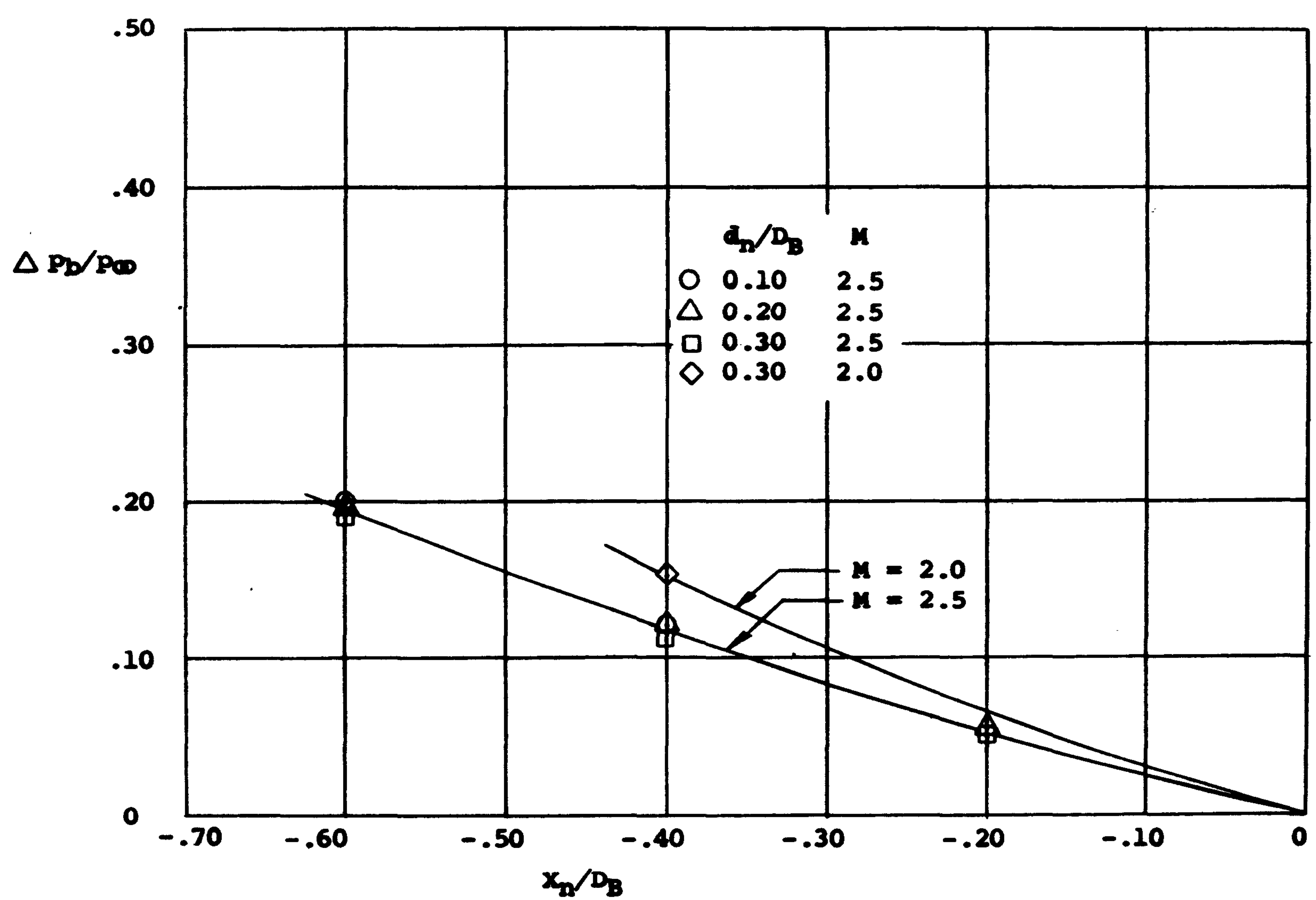


Figure 12. Increase in Base Pressure Ratio Due To Aft Nozzle Position.

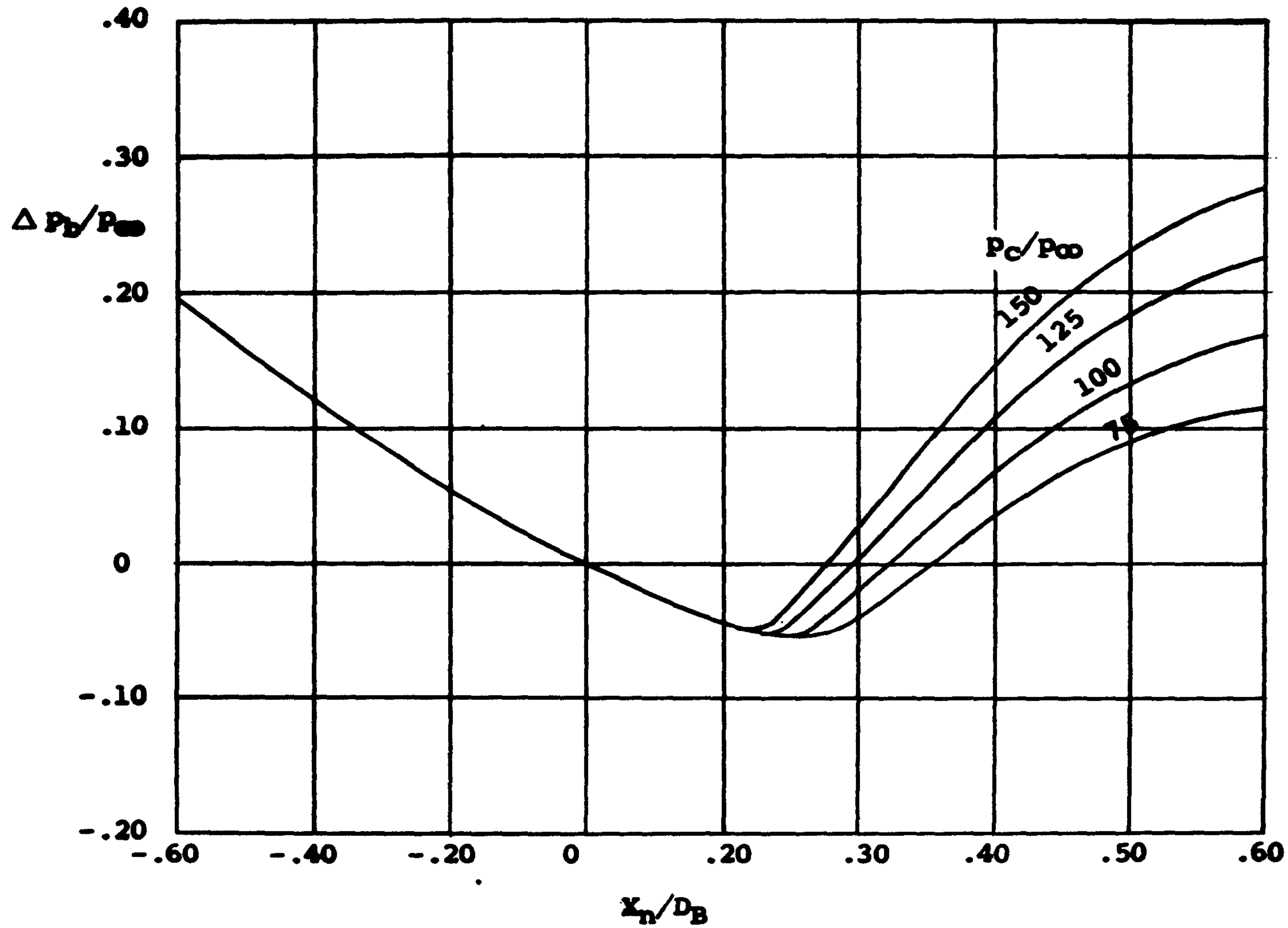


Figure 13. Incremental Change in Base Pressure Ratio Due to Sustainer Nozzle Position $M = 2.5$; $d_n/D_B = 0.20$

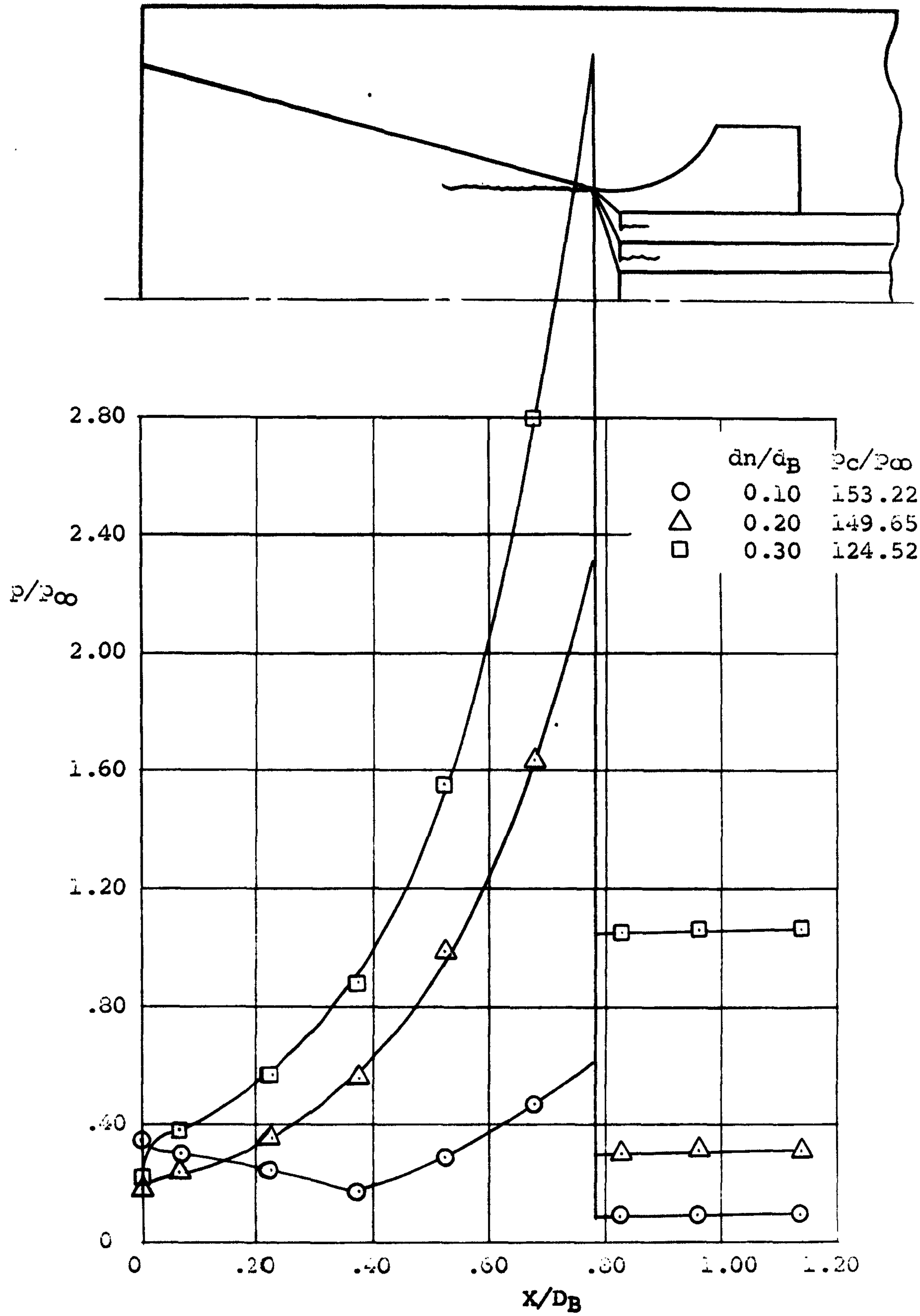


Figure 14. Effect of Sustainer Nozzle Diameter Ratio on Local Pressure Distribution. X_n/D_B = .8245; M = 2.5

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APPROVED

James H. Henderson

JAMES H. HENDERSON
Chief, Analysis Section

Raymond A. Deep

RAYMOND A. DEEP
Chief, Aerodynamics Branch

William C. McCorkle Jr.

WILLIAM C. MCCORKLE, JR.
Director, Adv Sys Lab, FMSD

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